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Sustainable Hybrid Epoxy Composites Reinforced with Hemp Fiber Coir and Nano Egg Shell Particle for Biodegradability Evaluation

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Abstract. Sustainable applications like, biodegradable packaging, aerospace and automotive industries are objective of this study's efforts to enhance and evaluate novel hybrid composite substances utilizing Hemp, Coir, and Nano Egg Shell Particle (NESP) as reinforcements at epoxy polymer matrix. The unique aspect of this work is the lack of prior research on composite systems that combine natural fiber (Hemp), bio-ceramic reinforcement (NESP), and an agro-waste filler (coir). In order to test the mechanical, thermal, biodegradability, and water absorption characteristics of five distinct compositions, we kept the epoxy content constant and varied the hemp fiber (25-5%), coir powder (5-25%) and nano egg shell particle (5%). For the composites, the production process began with hand lay-up and ended with hot pressing. In terms of tensile strength (44 MPa), flexural strength (87 MPa), and maximum hardness (90.5 Shore D), the sample that contained 25% hemp, 5% coir, and 5% nano egg shell particle had the best results. On the other hand, samples that had a higher Coir content were more suitable for environmentally friendly uses since they were more biodegradable (losing up to 18.2% of their weight) and absorbed more water (7.1% after 72 hours). Reinforcing all samples with nano egg shell particles greatly improved their thermal stability. Composites with the best combination of biodegradability, mechanical durability and environmental sustainability can be achieved by precisely controlling the reinforcing content, as shown in the study. A fresh approach to creating environmentally friendly composites with various uses has emerged with this integrated reinforcement system, which draws on both natural and waste-derived materials.

1 Introduction

Natural fiber-reinforced polymer composites (NFRPCs) garnered significant interest on recent decades owing to distinctive combination of lightweight characteristics, sustainability, superior specific strength and cost efficiency relative to traditional synthetic fiber composites.

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The epoxy composites reinforced with nanoparticles and coir fiber such as fly ash and TiC were examined. Mechanical, thermal, and water absorption tests showed significant improvements due to strong filler–matrix interaction and uniform dispersion. Thermogravimetric analysis confirmed good thermal stability, with water absorption increasing as reinforcement content increased [1]. Four composite samples with varying proportions of biochar, rice bran, and coconut coir in an epoxy matrix were tested. Sample B (20% biochar) showed the highest stiffness, while samples with rice bran or coir exhibited reduced or mixed mechanical performance [2]. Biocarbon produced from hemp and switchgrass (450–650°C) was incorporated (10–20 wt%, 50–100 µm) into hemp fiber bio-epoxy composites to study water absorptivity. Higher pyrolysis temperature (650°C) and larger particle sizes minimized swelling, while smaller sizes reduced diffusivity and higher filler loadings decreased tensile energy due to agglomeration [3]. Epoxy composites were fabricated using sisal fibers (SF) and −43 µm eggshell particles (ESP) in both calcined and uncalcined forms, followed by SEM/EDS and XRD characterization. Mechanical tests showed that uncalcined ESP/SF composites performed better due to preserved $CaCO_3$ structure and superior interfacial behavior. Across varying loadings, 3 wt.% ESP provided the most optimal overall mechanical performance [4]. Composites reinforced with 20 wt.% alkali-treated Moringa husk fibers and nano-SiC (1–5 wt.%) were evaluated for mechanical, tribological, and water absorption behavior. The composite with 4 wt.% nano-SiC achieved the highest tensile (+23.11%), impact (+23.22%), hardness (+14.86%), and flexural (+9.6%) improvements over the SiC-free specimen [5]. Hybrid polyester composites reinforced with areca and tamarind fibers (40 wt.%) and SiC nanoparticles (1–4 wt.%) were tested for thermo-mechanical, wear, and hygro-aging behavior. The 3 wt.% SiC composite showed the best overall properties, including tensile (9.137 MPa), flexural (104.056 MPa), impact (7.983 J/cm^2), high hardness (91.577 HRRW) and thermal stability (360°C) [6]. Polypropylene hybrid composites reinforced with short woven flax, basalt fibers, and rice husk powder were manufactured using extrusion and injection molding. With MAPP compatibilizer, tensile strength improved by 57.68%, flexural strength by 52.59%, and tensile modulus by 147%, supported by DMA showing a 129% rise in storage modulus [7]. Hybrid natural fiber composites using alkali-treated rice husk and sun hemp were analyzed for mechanical, thermal, and pyrolysis behavior. FTIR, XRD, and TGA revealed enhanced crystallinity and improved thermal response with sun hemp–rice husk composites showing lower activation energy than single-fiber rice husk composites. Findings highlight the value of hybrid agro-waste reinforcements for better structural properties and improved pyrolysis performance [8]. Hybrid epoxy composites reinforced with Luffa aegyptica and bagasse fibers were produced at varying fiber loadings (5–25 wt%). Mechanical tests (compression, tensile, flexural) and SEM showed that the luffa–bagasse blend achieved superior compression strength compared to individual fiber composites. The research shows the possibility of utilizing agricultural waste fibers in a mixture to increase mechanical behavior and develop sustainable composites [9]. According to literature review there are no past studies that have thoroughly investigated the usage of hemp fiber, Coir and Nano Egg Shell Particle in a three phase epoxy composite. This paper will therefore attempt to prepare and characterize five different formulations of various proportions of hemp and Coir, with Nano Egg Shell Particle holding constant, and then test each of these formulations comprehensively in terms of biodegradability, thermal, mechanical and water absorption. The study stands a chance of establishing the most appropriate solution to enhancing the durability-environmental friendliness of multifunctional composites. Its novelty at demonstrating that, by trading off ratios of three reinforcing components, it is possible to prepare composites with a variety of efficiency profiles blended and matched to fit specific applications, such as biodegradable packaging, thermally stable aerospace parts or high-strength automotive parts.

This work does not push field of hybrid biocomposites a notch higher offers lasting solution to the issue that has always been how to make good use of agricultural waste streams without necessarily using petroleum based products that are harmful to the environment.

2 Materials and Methods

Hemp fiber, coir fiber powder, and NESP-reinforced polymer composites multi-stage manufacturing are controlled in various steps. These processes entail extraction of the raw materials, chemical treatment of the materials, conditioning of the particle sizes, reinforcement dispersions and lastly, the composite is manufactured. In order to remove hemicellulose, surface lignin levels, pectins, waxes and other amorphous impurities, hemp fibers are alkali treated by dipping them in a 5% solution of NaOH 24 hours at room temperature. While larger alkali concentrations (>10%) are known to produce excessive fibrillation and cellulose degradation, this concentration is generally considered ideal since it improves surface roughness and increases interfacial adhesion with epoxy. Inadequate matrix-fiber bonding and partial delignification are common outcomes of concentrations below 5%. It is necessary to wash the fibers multiple times until they reach a neutral pH after treatment, and then to dry them in oven on 80°C for 6 hours to eliminate any binding moisture. Achieving better homogeneity and filler-matrix dispersion requires converting coir fiber from its native fibrous form into coir fiber powder. Drying in the shade for 24 to 48 hours follows a washing to remove soluble contaminants and dust from raw coir. To get homogenous coir powder with regulated size of 50-100 μm, which were chosen to ensure enough surface area, better dispersibility, and consistent mechanical interlocking within the polymer matrix, the dried material is mechanically shredded and then ball-milled. As the coir-based products are hygroscopic in nature and have high lignocellulosic content, it is sieved and stored in an airtight container to prevent the absorption of moisture. Nano Egg Shell Particles (NESP) is a secondary reinforcement, commonly in the fine particle form which should have a particle size of 10-50 um based on the supplier. The NESP powder is mixed after being dried in an oven at 110 deg C and a period of 12 hours to ensure that moisture content and aggregation rates are at a zero level. The transfer of stress between filler particles and epoxy matrix in the selected size range can be achieved more efficiently, and surface activity can be controlled and dispersed as well. Epoxy resin is combined with alkali-treated hemp, micronized coir fiber powder and NESP, which are then mixed using mechanical stirring to ensure that the reinforcement ingredients are mixed evenly. The next processes in the casting of the composite mixture are hand lay-up and compression curing that enhance mechanical performance and structural integrity. Five compositions can be made using a constant polymer matrix with a different weight percentage of hemp fiber, coir fiber powder, and Nano Egg Shell Particle. Table 1 provides the composition of materials that were used in the production of composites utilized in this study. The materials had to be mixed in stages so that agglomeration would not occur, and the reinforcements would be consistent. First, the constant mixing of the epoxy resin was done at a magnetic stirrer during 30 minutes during the addition of the following powders in increasing quantity: nano egg shell particle (10-50 μm) and coir (50-100 μm). Subsequently, the particle fillers were ultrasonicated to 20 minutes so as to dissolve any aggregates and in order to disperse the particles uniformly [10]. After that, hemp fibers that were treated with alkali in small bundles were resin-filled with resin-filler mixture stirred at a lower rate of 200 rpm. This enabled every batch of fibers to be well moistened then add more. This step by step fiber addition was necessary in order to promote even distribution and prevent clustering of fibers. Then hardener was slightly added before pouring the slurry into molds. After adding to it, hardener with added to induce cross-linking and resulting liquid, it was then poured into mold previously covered with release agent.

In the case of composites, hand lay-up process guarantees uniform thickness and reinforcement density with the hand-laying of consecutive layers of fiber-reinforced resin [11]. The compression of the mold using 120°C at 5 MPa is sufficient in order to guarantee that it is cured properly and shows minimal creation of voids.

Table 1. Composition of hybrid composites epoxy

Sample Code	**Hemp Fiber (wt. %)**	**Coir (wt. %)**	**Nano Egg Shell Particle (wt. %)**	**Epoxy Resin (wt. %)**
A	25	5	5	65
B	20	10	5	65
C	15	15	5	65
D	10	20	5	65
E	5	25	5	65

The composite specimens were removed out of the mold following post-cure of the samples at the oven set at 80C which took six hours. Mechanical, thermal and biodegradability test demand standard shaped cuts of the composite samples achieved after doing. The sweet point in terms of wear resistance, environmental friendliness and mechanical strength can be located by simply scrutinizing the composites of varying reinforcement contents produced. Green composites as an environmentally friendly material would be applicable in areas like transport, planes and biodegradable containers. Following ASTM guidelines, the manufactured composites undergo tensile, flexural, and hardness tests to evaluate their mechanical characteristics. The ASTM D638 standard specifies the use of a universal testing machine (UTM) capable of withstanding loads up to 50 kN for the tensile strength test [12]. The specimen has the physical characteristics of a dumbbell, measuring 165 × 13 × 3 mm. To measure composite's ability to withstand axial stresses, this test calculates its ultimate tensile strength, elongation at break, and Young's modulus. In order to ascertain the flexural strength and modulus, the UTM was bent in three point test as per ASTM D790 with the help of same UTM. The specimens of 127 × 12.7 × 3 mm are placed at two spans and subjected central stress till they break. To test the hardness of the composite in compliance with ASTM D2240 we test the hardness of Shore D with a hardness tester. Of significance in its potential applications, the test ascertains the indentation resistance of the composite which in turn ascertains its durability and abrasion resistance. ASTM E1131 requires the use of a thermogravimetric analyzer (TGA) to determine the stability of the composites during heating. These samples are 10-15 mg heated in a nitrogen atmosphere between room temperature and 800 o C at a rate of 10 o C/min. The test measures the deterioration behavior, weight loss as a function of heating, and temperature of breakdown. Soaking composite samples in deionized water on ambient temperature for 24 to 72 hours were the standard process for assessing water absorption, as per ASTM D570. Sizes of 25 mm × 25 mm × 3 mm were the measurements of the samples. We can assess the composite's water resistance by tracking the proportion of weight gain. To determine biodegradability, samples are typically composted at 58ºC for 30 days, in accordance with ASTM D5338 standards. By monitoring the rate of weight loss, which is a measure of breakdown rate, we may determine if the composite is biodegradable. Tonset, or the beginning of degradation, was defined as the point where the baseline and tangent at steepest slope of TG curve met. Reaching peak of derivative thermogravimetric (DTG) curve enabled us to determine the maximal degradation temperature (Tmax). Calculation of the char yield were based on percentage of weight maintained at 800ºC. Values, over three separate runs, were shown by the standard deviation and mean.

3 Results and Discussions

3.1 Tensile Test

In order to determine the composite's strength at different reinforcing levels, the prepared hybrid composites undergo mechanical testing. The tensile test yields useful data regarding the mechanical properties of composites made with different reinforcing percentages. Fig. 1 shows that the tensile strength drops as the percentage of Coir increases, while the quantity of Nano Egg Shell Particle remains constant at 5%, and the matrix is epoxy resin. E (15% Hemp, 25% Coir, 5% Nano Egg Shell Particle, 65% Epoxy) has the lowest strength at 30 MPa, while A (25 % Hemp, 5% Coir, 65% Epoxy) achieves the maximum tensile strength at 44 MPa. Another study found that mechanical testing using 6 wt% TiO_2 yielded the highest results. The top-performing E-type laminate, which consisted of 30% hemp, 7% jute, 57% epoxy, and 6% TiO_2, achieved gains of approximately 24-25% in tensile, flexural, and impact strength [13]. Since hemp adds a lot to the composite's strength and tensile reinforcement, the pattern implies that its presence has a big impact on its tensile strength.

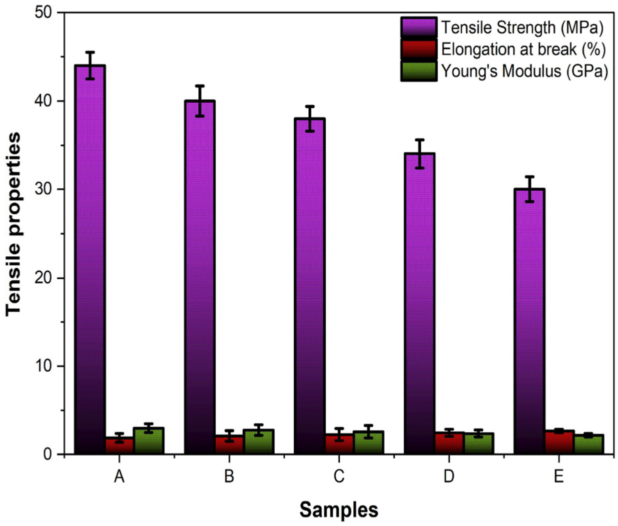

Fig. 1. Tensile behaviour of the composites.

Tensile strength values drop as the percentage of hemp fiber decreases from 25% in A to 5% in E. This is because overall load- capacity drops. In contrast, the elongation at break goes up from 1.9% at A to 2.6% at E, suggesting more flexibility as a result of the increasing Coir powder content. This filler does not really add much to the tensile load resistance, but it does increase flexibility. Reducing quantity of hemp fiber makes composite more ductile as Young's modulus reduces 2.9 GPa at A - 2.2 GPa at E. All of the samples have had 5wt% Nano Egg Shell Particle added to them to increase their hardness and wear resistance, and the reinforcement is well-adhered to each other thanks to the 65wt% epoxy resin matrix. B (20wt% Hemp, 10wt% Coir, 5wt% Nano Egg Shell Particle, 65% Epoxy) is the optimal composition for uses requiring both durability and good flexibility, according to the test results, since it strikes the best balance between the two properties. Composites' mechanical properties of the composites can be better understood by looking at their SEM fractography results, which reveal important details about the composites' interfacial bonding, fiber dispersion, and failure causes.

Fig. 2 shows the SEM results of the composites. The increased tensile strength of the composite's was a result of the stronger interfacial bonding among polymer matrix and hemp fiber, coir fiber powder, nano egg shell particle, and epoxy resin, which made up the remaining 65wt%. The scanning electron micrographs reveal good fibers- Matrix bonding and high resin infiltration due to the low void content and even distribution of fibers in the scanning electron micrographs. The interfacial bonding of the composites was confirmed by SEM examination [14]. By bolstering network polymer with secondary fillers—representing waste from coir fiber powder—Nano Egg Shell Particles improved load transfer efficiency, reduced stress concentration sites and prevented microcracking.

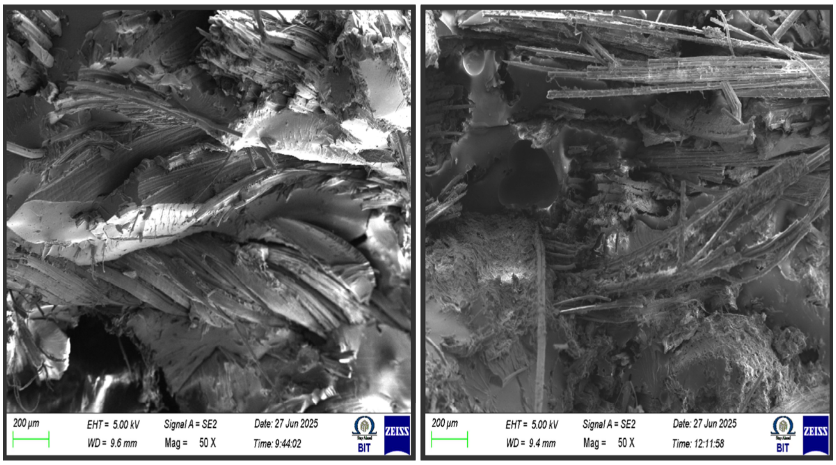

Fig. 2. SEM images of Hemp fiber and coir powder.

Similarly, the composite containing 5wt% hemp fiber, 25wt% coir powder fiber, 5wt% nano egg shell particle, and 65wt% epoxy resin showed an extra boost in ductility due to the evenly distributed coir particles in the matrix. The SEM micrographs show that the adhesion between the epoxy resin and reinforcements has improved, as there are fewer fiber pull-outs and more matrix continuity. The energy dissipated under tensile stress was able to prevent premature fracture due to the greater waste percentage of coir powder. Particles of Nano Egg Shell also improve fracture strength by preventing cracks from growing. With better interactions among the polymer and fiber, even distribution of stress, and less interfacial defects throughout the composite structure, facts imply that mechanically optimized composite composition has better mechanical characteristics.

3.2 Flexural Test

Fig. 3 shows results of the flexural tests, which reveal that the flexural strength and modulus gradually drop as the hemp fiber concentration decreases and the Coir content increases in the composite. Combination A (with 25% hemp, 5% coir, 5% nano egg shell particle, and 65% epoxy) has a maximum flexural strength of 87 MPa, whereas combination E (with 25% hemp, 25% coir, 5% nano egg shell particle, and 65% epoxy) has a minimum value of 65 MPa. This proves that hemp fiber plays a critical role in increasing the composite's load-carrying ability when subjected to flexural stress. Additionally, because Coir has a reduced mechanical strength, its higher integration reduces structural stiffness.

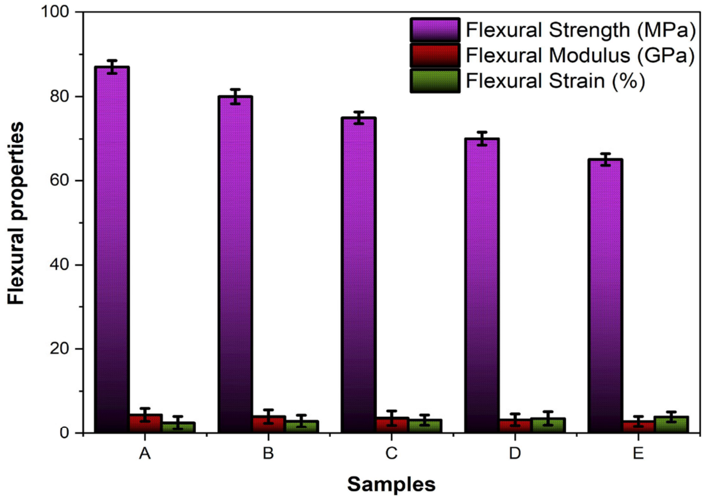

Fig. 3. Flexural behaviour of the composite samples.

Additionally, the flexural modulus decreases from 4.4 GPa (A) to 2.87 GPa (E), confirming once again that a higher hemp content guarantees a stiffer and more rigid material. Composites with a higher Coir content are pliable but weaker due to an increase in flexural strain from 2.53%b (A) to 3.94% (E). The homogeneous reinforcement of 5wt% Nano Egg Shell Particles ensures structural stability by imparting hardness and wear resistance. B (20wt% Hemp, 10wt% Coir, 5wt% Nano Egg Shell Particle, 65wt% Epoxy) is an excellent choice among the samples because it combines strength and flexibility in a balanced way, making it ideal for uses that demand mild flexibility and mechanical durability. The TS of hybrid composites were more than that of epoxy composites made solely of hemp, which normally vary from 40 to 55 MPa based on loading and treatment of the fibers. Also, as compared to coir fiber powder-reinforced composites, which typically have a flexural strength limit of 25–35 MPa owing to poorer interfacial bonding, there were noticeable gains in this area. The findings indicate that Nano Egg Shell Particle coupled with hemp and coir enhances transmission of loads and resistivity to crack in a synergistic manner. In another study, hand layup was applied after fiber preparation using NaOH and retting in order to produce epoxy composites that were reinforced with powdered chick eggshell and Kenaf fiber (calcined/uncalcified). Mechanical tests were better in uncalcined eggshell-kenaf composites, with a tensile strength of 49.57 MPa, flexural strength of 34.41 MPa, and impact energy of 16.43 kJ/m 2, compared to calcified ones [15]. More importantly, biodegradability of composites were similar to that of the coir fiber powder-only systems but greater than that of hemp-only systems, demonstrating that Coir addition did not compromise strength and also significantly enhanced eco-friendliness.

3.3 Hardness of the Composite

Fig. 4 shows the results of hardness tests run on the Shore D scale; as the Coir content in the composite increases and the hemp fiber content decreases, the hardness decreases in a predictable way. E (5wt% Hemp, 25wt% Coir, 5wt% Nano Egg Shell Particle, 65wt% Epoxy) has the lowest hardness value of 82.3, whereas A (25wt % Hemp, 5wt% Coir, 5wt% Nano Egg Shell Particle, 65wt% Epoxy) has the maximum hardness value of 90.5.

This pattern of behavior indicates that the inclusion of hemp fiber considerably improves the composite's surface strength and indentation resistance. On the other hand, the composite becomes softer with a higher Coir content because of its organic and less rigid characteristics.

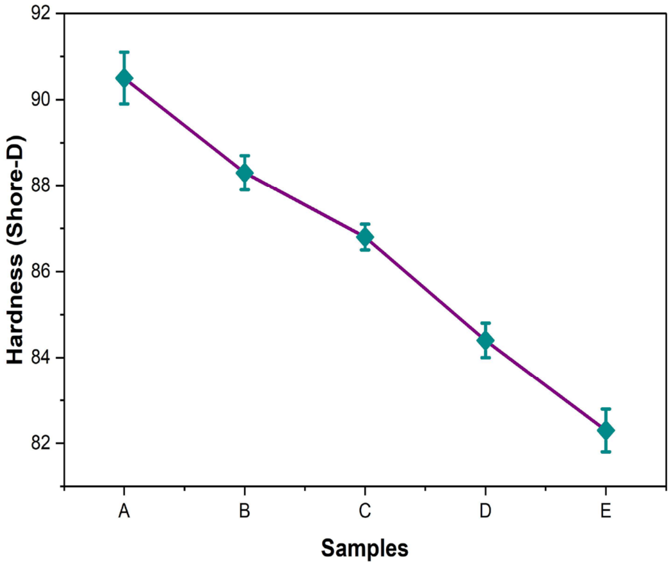

Fig. 4. Hardness of the fabricated composites.

Increasing the coir percentage in the higher-numbered samples slightly cancels out the advantage of adding Nano egg shell particle (5 wt%), which improves the hardness and wear resistance in all samples. With a hardness of 88.3 and an ideal combination of structural strength and moderate flexibility, B (20 wt% Hemp, 10 wt% Coir, 5 wt% Nano Egg Shell Particle, 65 wt% Epoxy) is an extraordinary material. When looking at composites for uses requiring high hardness and durability, the results show that those with a higher hemp fiber content perform better. Composites with a larger Coir content, on the other hand, degrade more easily and are more pliable, but they become less rigid.

3.4 Biodegradability of the Composites

Composite samples show a steady decrease in weight after 30, 60, and 90 days in the biodegradability test, demonstrating that the Coir content affects the rate of decomposition. Weight losses of 4.1% after 30 days, 5.1% after 60 days, and 10% after 90 day indicate that composite A—consisting of 25 wt% hemp, 5 wt% coir, 5 wt% nano egg shell particles, and 65wt% epoxy—displays the lowest biodegradability, as shown in Fig. 5. With a weight loss of 7.8% after 30 days, 13.2% after 60 days, and 18.2% after 90 days, E (5 % Hemp, 25% Coir, 5% Nano Egg Shell Particle, 65% Epoxy) demonstrates the highest degradation rate.

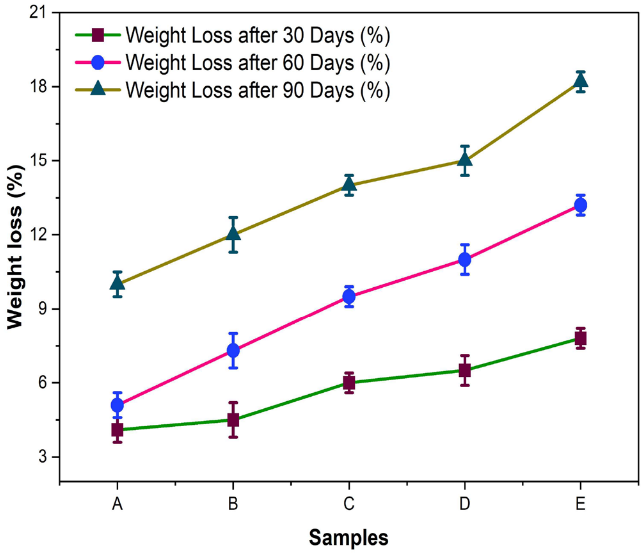

Fig. 5. Loss of weight of the composites by biodegradability.

According to this pattern, the biodegradability of a material rises as its Coir content rises and falls as its hemp fiber content rises. Organic filler, coir breaks down more quickly due to its high concentration of microbially degradable materials such as cellulose, hemicellulose, and lignin. Hemp fiber, on the other hand, slows degradation by adding structural stability and elasticity. The composites are marginally more decomposable than materials based on pure biopolymers due to the addition of Nano Egg Shell Particle, which increases wear resistance and hardness. Biodegradable packaging and environmentally friendly applications that require decomposability after a specific period are better served by composites with a greater Coir content (D and E). Parts for automobiles or airplanes, which need to last a long time and have a low biodegradability rating but still need to be strong mechanically, would benefit more from composites made with higher hemp fiber content (A and B). The results highlight the potential of hybrid composites as a material for manufacturing environmentally friendly products across several sectors, since they can achieve mechanical strength while also being sustainable.

3.5 Water Absorption

Results from water absorption tests, as illustrated in Fig. 6, reveal a rising of water uptake over 24 to 72 hours, higher Coir contents the composite showing superior absorption. At 24, 48, and 72 hours, the water absorption rates of Composite A—a mixture of 25wt% hemp, 5wt% coir, 5wt% nano egg shell particle, and 65wt% epoxy were the lowest at 2.3%, 3.3%, and 4.3%, respectively. The mixture with the maximum water uptake, E (5wt % Hemp, 25wt% Coir, 5wt% Nano Egg Shell Particle, 65wt% Epoxy), reached values of 4.3%, 6.3%, and 7.1% in the same time periods.

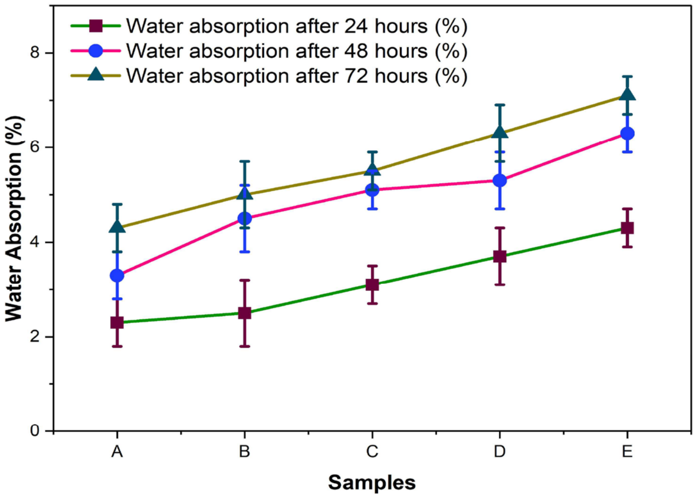

Fig. 6. Water absorption of the composites.

Organic fillers, such as cellulose and lignin, have a hydrophilic nature and can readily absorb water, which is why Coir has a positive effect on water uptake. Despite being a natural fiber reinforcement, hemp fiber outperforms Coir in terms of moisture resistance and contributes to lower water absorption in samples that contain more hemp fiber. Each sample has superior thermal stability and toughness thanks to the 5wt% Nano Egg Shell Particle reinforcement. Because it is inorganic and has few interactions with water, its effect on water absorption is minimal at best. To assess how the hybrid epoxy composites were affected by heat, TGA were used. Among thermal parameters measured are the char yield at 820℃, the maximum degradation temperature (Tmax), and the onset degradation temperature (Tonset). As a whole, these numbers are in Table 2, which is based on three independent testing. These findings give light on how Nano Egg Shell Particle stabilizes composites and how loading hemp fiber and Coir affects thermal stability. The results show that as the Coir concentration increased, the composites' thermal stability declined. With a Tonset of 278℃ and a Tmax of 368℃, A demonstrated exceptional thermal resistance, since it included the largest hemp component (25 wt %). This is because hemp fibers contain a lot of cellulose, which, at lower temperatures, breaks down into smaller pieces that are more easily broken down by heat. The decrease in Tonset and Tmax was proportional to the rise in Coir concentration in B-E. Composite E had the lowest values (Tonset = 245 ◦C, Tmax = 335 ◦C), which is in line with the fact that coir fiber powder contains hemicellulose and lignin, which are not as thermally stable as cellulose. Tonset and Tmax have been steadily decreasing throughout the series, which shows that the hybrid composites are quite sensitive to fiber-to-filler ratio. In addition, the char yield results corroborate these findings. Decreases in Tonset and Tmax, char yields of all composites were reasonably high, ranging from 23wt% to 30wt% by weight. At 820°C, composite A had the largest char yield (29.2 wt%), whereas composite E retained 23.5wt%. The consistent 5wt% Nano Egg Shell Particle content in all of the formulations is responsible for the low variability in char yield among the samples. By adding a bio-ceramic filler that is thermally stable and does not breakdown under the conditions examined, Nano Egg Shell Particle improves char residue and adds composites' overall thermal resistance. Even most biodegradable formulation (E) managed to preserve over 20% of its mass at increasing temperatures, due to this effect, which mitigated the impact of Coir's greater volatile content. These data clearly show that biodegradability and thermal stability are not mutually exclusive.

Confirming cellulose's greater heat resistance, higher hemp loading improved Tonset and Tmax. Composites with a high Coir content were more environmentally benign and biodegradable, although they were less thermally stable. The continuous addition of Nano Egg Shell Particles had a stabilizing effect by guaranteeing substantial char development; this preserved the composites' capability for thermal and semi-structural applications. Tri-phase hybrid composites showed a good balance between thermal resistance and biodegradability, according to TGA data.

Table 2. Thermogravimetric analysis of the composites

Specimen	**Char yield at 800ºC (wt. %)**	**Tmax ('C, DTG peak)**	**Tonset (ºC)**
A (25 H/5 Coir/ 5 Nano Egg Shell Particle/65E)	29.2 ± 0.9	368 ± 2.5	278 ± 4.5
B (20H/10 Coir / 5Nano Egg Shell Particle/65E)	27.3 ± 0.8	362 ± 4.5	273 ± 5.3
C (15H/15 Coir / 5Nano Egg Shell Particle/65E)	26.1 ± 0.6	355 ± 3.9	265 ± 5.1
D (10H/20 Coir / 5Nano Egg Shell Particle/65E)	25.2 ± 0.5	345 ± 6.1	255 ± 7.9
E (5H/25 Coir / 5Nano Egg Shell Particle/65E)	23.7 ± 0.9	335 ± 4.9	245 ± 6.2

The results show that a combination of Coir, nano egg shell particles, epoxy, and hemp reduces Tonset and Tmax in a regulated way while keeping char yields relatively high. Composites made from a combination of biodegradable fillers, bio-ceramic particles, and natural fibers provide a strong medium between ecological responsibility and practical performance; this proves the efficacy of the design approach. Because of the crucial need of dimensional stability in humid settings, structural applications like automotive and aerospace parts benefit from composites with lower water uptake (A and B). When it comes to biodegradable packaging and green applications, composites with a higher Coir content (D and E) are ideal because of their controlled moisture uptake, which makes disintegration easier. This study's results back with previous research showing that the composition of reinforcements affects thermal, biodegradability and mechanical properties of polymer composites. The mechanical outcomes reveal that a combination of 25wt% hemp, 5wt% coir, 5wt% nano egg shell particle, and 65wt% epoxy yielded the best tensile and flexural qualities. Hemp fibers' microstructural function in stress transfer at the fiber-matrix contact and their abundance of crystalline cellulose provide an explanation for this behavior. In order to improve interfacial bonding and load transfer, alkali treatment of hemp increased exposed hydroxyl groups and surface roughness. Previous research has linked mechanical reinforcement to enhanced fiber-matrix adhesion in natural fiber composites. Increased Coir loading, decreased strength due to filler particle adherence to epoxy being weaker and Coir's increased hemicellulose and lignin content, which causes it to disintegrate sooner and interact poorly with the matrix. Coir improved ductility and flexibility while decreasing tensile and flexural strength. Coir was able to absorb strain and postpone catastrophic failure due to its somewhat amorphous nature, which generated localized deformation zones. The B and C composites showed intermediate strength and increased strain tolerance is because they were able to strike a compromise between strength and flexibility. Rigid bio-ceramic particles served a micro-load-bearing sites, increasing hardness and limiting the mobility of polymer chains; this clearly demonstrated the significance of Nano Egg Shell Particle. As shown in thermogravimetric study, which verified that all composites maintained 22-26 wt % mass, their thermal stability had a role in increased char yields.

The biodegradability study emphasizes how Coir speeds up the breakdown procedure. The Coir content of the composite (D and E) increases, the faster it decomposed because the organic filler encourages microbial activity. Further evidence for this finding comes from the data on water absorption: samples with a higher Coir content absorbed more water, which in turn encouraged the colonization and breakdown of microbes. There is a clear trade-off between strength and biodegradability, since increased water absorption reduced mechanical integrity. This is why structural load-bearing usage are more suited for hemp-rich composites, whilst packaging applications are better suited for high-Coir composites. Findings on thermal stability provide more evidence of the significance of reinforcement synergy. The cellulose crystallinity in hemp fibers caused the Tonset and Tmax values to be higher, whereas the thermal instability of the hemicellulose and lignin in Coir caused them to be lower. Nano Egg Shell Particle stabilization of the temperature response through resistance to decomposition and promotion of residue formation occurred despite this decrease. Despite differences in fiber/filler ratios, the consistent char yields across all tests demonstrate that Nano Egg Shell Particle stabilizes the mixture. Consistent with previous research on bio-ceramic-filled epoxy systems, our results show that the high thermal conductivity and barrier effect of Nano Egg Shell Particle particles enhance the thermal stability and hardness of the material. The increased adhesion and load transfer properties of hemp fibers make them more stiff and strong. At the cost of strength, coir adds ductility and speeds biodegradability. By limiting the mobility of polymers and encouraging the development of char, nano egg shell particle particles add toughness and thermal stability. Therefore, the triple phase hybridization solution is a compromise among mechanical strength, environmental friendliness and thermal of composites. The results also indicate novelty of the research and shows that one of the possible solutions to produce environmentally friendly hybrid composites according to the particular use is to combine natural fibers with bio-ceramic reinforcements and biowaste fillers.

3.6 Environmental Impact Assessment (Life Cycle Analysis & Recyclability)

The proposed sustainable hybrid epoxy composite reinforced with hemp fiber, coir, and nano eggshell particles demonstrates significant potential for reduced environmental impact compared to conventional synthetic composites. A Life Cycle Analysis (LCA) of the material spans raw material extraction, processing, usage, and end-of-life stages. In the raw material phase, hemp and coir fibers are renewable, biodegradable, and require relatively low energy, water, and chemical inputs during cultivation. Their use also contributes to carbon sequestration. Eggshell particles, derived from agro-waste, promote waste valorization and reduce landfill burden. This phase has a notably lower environmental footprint than petroleum-based fiber production. During the manufacturing stage, energy consumption arises from fiber treatment, epoxy matrix preparation, and composite fabrication. Although epoxy resin is petroleum-derived and non-biodegradable, the incorporation of natural fibers and waste-derived nanoparticles reduces the overall resin content, thereby lowering embodied energy and emissions. In the use phase, the composite offers durability, corrosion resistance, and lightweight properties, leading to energy savings in applications such as automotive or construction. The enhanced mechanical performance from hybrid reinforcement can extend service life, reducing the need for frequent replacement. The end-of-life stage presents challenges due to the thermoset epoxy matrix, which is not easily recyclable. However, the presence of natural fibers improves partial biodegradability under controlled conditions. Mechanical recycling (grinding and reuse as filler) and thermal recovery (energy extraction) are feasible options. Additionally, ongoing research into bio-based or recyclable epoxy systems can further enhance sustainability.

From a recyclability perspective, while full recyclability is limited, the composite supports circular economy principles through waste utilization (eggshells), reduced reliance on synthetic fibers, and potential for downcycling. Overall, the hybrid composite exhibits a reduced carbon footprint, improved resource efficiency, and partial biodegradability, making it an environmentally favorable alternative to conventional composites, with future scope for fully green matrix development.

4 Conclusion

The research was successful in meeting the objectives as it developed and described the eco-friendly hybrid epoxy composites that are reinforced with nano egg shell particles (NESP) as well as the coir and hemp fiber. The fabrication of five different formulations was possible based on a variable 5wt% Nano Egg Shell Particle and 65wt% epoxy content where the Hemp and Coir proportions of the fabricated formulations could be 5-25wt%. Composites with varying percentages of hemp, coir, and nano egg shell particles (A) showed the best results in mechanical testing, with a TS of 44 MPa, FS of 87 MPa, and Shore D of 90.5. This confirms that the surface resistance and load-bearing capacity are both improved with increasing hemp content. An increase in Coir was associated with a decrease in Young's modulus 2.9 GPa (A) to 2.2 GPa (E) and an increase in elongation at break from 1.9% to 2.6%. With weight losses of 7.8% after 30, 60%, and 18.2% after 90 days, respectively, in the E (5wt% Hemp, 25wt% Coir) mixture, the biodegradability test confirmed that Coir accelerates decomposition. Because Coir is a hydrophilic filler, its water absorption increased with increasing Coir concentration; after 72 hours, it went from 4.3% in composite A to 7.1% in E. Using thermal stability analysis, we found that all of the samples were more resistant to heat degradation when Nano Egg Shell Particles were present. With 20wt% hemp, 10wt% coir, and 5wt% nano egg shell particle, the composition of the composite B was able to strike a decent balance between, mild biodegradability, thermal performance and mechanical durability. These results provide more evidence that customized hybrid composites can replace more traditional materials in transportation, biodegradable packaging and aerospace industries. To further improve thermal stability, wear resistance and mechanical strength, future research could investigate the introduction of nano-Nano Egg Shell Particle particles, which have a bigger surface area and superior dispersion capabilities. Furthermore, Coir can have its filler-matrix compatibility improved through physical or chemical treatments with Nano Egg Shell Particles. This can lead to improved mechanical qualities, less moisture absorption, and maintained biodegradability. The real-world performance of the composites could be better understood by conducting long-term weathering and environmental durability experiments. These studies would include subjects exposed to UV radiation and cyclic wetness. Following these paths will help create high-performance, environmentally friendly composites with a wide range of potential industrial and environmental uses.

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